TITLE: Self-Generation of Ultra-Short Pulses in a Cavity with a Dielectric Mirror Excited by an Array of Active THz Devices

Self-Generation of Ultra-Short Pulses in a Cavity with a Dielectric Mirror Excited by an Array of Active THz Devices

Lidiya Yurchenko, Vladimir Yurchenko

***Abstract* – We report on computer simulation of electromagnetic self-excitation in a cavity with a dielectric mirror and an array of active THz devices. Assuming the devices are sufficiently fast, we observed either continuous nonlinear oscillations or the trains of ultra-short pulses depending on the thickness and refractive index of the dielectric mirror.**

I. Introduction

We study self-excitation of electromagnetic oscillations in a cavity with a dielectric mirror and an array of active devices (Fig. 1). The array is simulated as a continuous layer of an active medium specified by its current-voltage characteristic of N-type similar to GaAs Gunn diodes (Fig. 2).

The devices are assumed operating in the THz band so that their response to electromagnetic oscillations is instantaneous if the typical frequency of oscillations is below 1 THz.

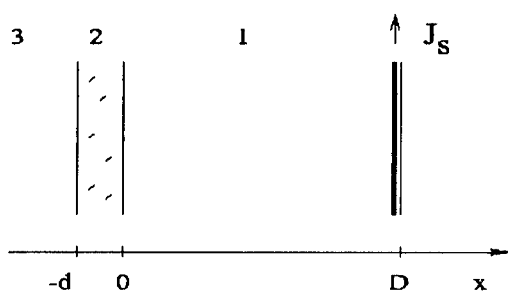

Fig. 1: Geometry of the problem

Coupling of the devices to the electromagnetic field is supposed to be sufficiently strong. In the case of an active layer, coupling is specified by the value of the surface current J_S excited in the layer by the electric field in the cavity E_Z.

In reality, coupling is more complicated, and the layer can represent different kinds of devices such as a matrix of diodes, FET transistors, semiconductor superlattices, Josephson junctions, etc [1].

When electromagnetic coupling is strong, self-excitation of anharmonic oscillations with transition to dynamical chaos is possible in the nonlinear system of this kind [2, 3]. It may have many applications, e.g., as a source of oscillations in emerging radar technologies such as a wide-band millimeter-wave noise radar [4].

In this paper, we present the results of our simulations of nonlinear oscillations in a cavity with a dielectric mirror. The latter is used for transmitting the electromagnetic signals from the cavity into the outer space. The dielectric mirror is also operating as a resonant filter when reflecting the electromagnetic field back into the cavity or transmitting it into the free space. So, the actual effect of the mirror is more complicated than simply providing the window for the electromagnetic radiation.

II. Formulation

We consider one-dimensional model of the cavity (Fig. 1) assuming the cavity width A being much greater than the length D.

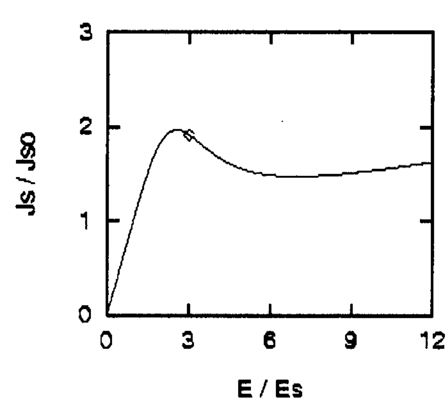

Fig. 2: Current-voltage characteristic of the devices

Nonlinear current-voltage characteristic of the active layer (Fig. 2) is approximated as

$$J_S = J_S(E) = J_{S0}G(E) =$$

$$J_{S0}\left[\left(E + 0.2E^4\right)/\left(1 + 0.2E^4\right) + 0.05E\right] \quad (1)$$

where $E = E(t) = E_Z(D,t)/E_S$ is the normalized electric field in the layer. The parameters are $J_{S0} = 50\,A/cm$ and $E_S = 1\,kV/cm$ where the carrier density $n = 10^{15}\,cm^{-3}$ and the frequency

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$f = 10\,GHz$ have been used to estimate the skin-layer thickness and hence the value of J_{S0} given above.
In the case of an array of active devices, we assume that the spacing between the devices is sufficiently small and the external voltage $V_0(t)$ is applied to every device in such a way that we can introduce the equivalent bias electric field $E_{Z0}(t)$ directed along the array. Then, we can consider the equivalent surface current density $J_S(t)$ that arises due to the total field $E_Z(D,t) = E_{Z0}(t) + E_{Z1}(D,t)$ where $E_{Z1}(D,t)$ is the microwave field excited at the wall $x = D$.
The electric field in the cavity, $E_Z(x,t)$, is a solution to the one-dimensional wave equation subject to the initial and boundary conditions. The boundary condition at the active layer $x = D$ is nonlinear and takes on the form

$$\left.\frac{\partial E_Z}{\partial x}\right|_{x=D} = -\left(\frac{W_0}{c}\right)\left(\frac{\partial J_S}{\partial E_Z}\right)\left.\frac{\partial E_Z}{\partial t}\right|_{x=D} \qquad (2)$$

where c is the speed of light, W_0 is the free-space impedance, and $J_S = J_S(E)$ is the surface current density defined above.
Eq. (2) follows from the generic boundary condition

$$H_y(D+0) - H_y(D-0) = J_S \qquad (3)$$

where $H_y(D+0) = 0$, H_y is the y component of the magnetic field that, due to the Maxwell's equations, satisfies the relation

$$\mu_0\left(\frac{\partial H_y}{\partial t}\right)\Bigg|_{x=D} = \left(\frac{\partial E_Z}{\partial x}\right)\Bigg|_{x=D}. \qquad (4)$$

Notice that the nonlinear factor dJ_S/dE_Z in Eq. (2) is the differential conductance of the active layer. The latter is negative when the total field $E_Z(D,t)$ falls in the negative differential resistance region.
Boundary conditions at the both sides of the dielectric mirror are linear and follow from the continuity of the tangential components of the electric field at the dielectric surfaces.
For the further analysis, we follow [2] and make use of the Riemann solution available to the one-dimensional wave equation. By considering the field in the cavity (i=1), in the dielectric mirror (i=2), and in the free space (i=3), we take the solutions

$$E_Z^{(i)}(x,t) = f_i(v_i t + x) - g_i(v_i t - x) \qquad (5)$$

where $f_i(.)$ and $g_i(.)$ are unknown functions, $v_{1,3} = c$ and $v_2 = c/n$, and apply boundary conditions at the active layer, at the surfaces of the dielectric mirror, and at infinity.
In this way, we arrive at the multiple delay difference equation as follows

$$f(\tau) = \{G\left[E_0^{(0)}\right] - (C_0/n_1)G\left[E(t,\tau,\tau_1,\tau_2,\tau_3)\right]\} + E_1(\tau_1,\tau_2,\tau_3) \qquad (6)$$

where

$$E(t,\tau,\tau_1,\tau_2,\tau_3) = E^{(1)}(\tau,\tau_1,\tau_2,\tau_3) + E^{(0)}(t), \qquad (7)$$

$$E^{(1)}(\tau,\tau_1,\tau_2,\tau_3) = n_1\left[f(t) - \eta^2 f(\tau_1) - \eta\, f(\tau_2) + \eta\, f(\tau_3)\right], \qquad (8)$$

$$E_1(\tau_1,\tau_2,\tau_3) = \eta^2 f(\tau_1) - \eta\, f(\tau_2) + \eta\, f(\tau_3), \qquad (9)$$

$E(t,\tau,\tau_1,\tau_2,\tau_3)$ is the total electric field in the active layer at the moment $t = (n\tau - D)/c$, $E^{(1)}(\tau,\tau_1,\tau_2,\tau_3)$ is the microwave field in the layer, $E^{(0)}(t)$ is the bias field defined by the Kirchhoff law of the bias circuit (if the latter contains the source E_{ext}, the load resistor R, and no reactive components, $E^{(0)}(t)$ is defined by the equation $E + RJ_S(E) = E_{ext}$), $E_0^{(0)}$ is the initial value of $E^{(0)}(t)$, $G_0 = W_0 J_{S0}/E_S$ (for the parameters given above, $G_0 \leq 20$), $\tau_1 = \tau - h$, $\tau_2 = \tau - L$, $\tau_3 = \tau - L - h$, $h = 2d$, $L = 2D/n$, $n_1 = n + 1$, and $\eta = (n-1)/(n+1)$.
The initial value of the field in the cavity, $E_Z(x,0)$, is chosen to be zero. The oscillations appear in response to a small fluctuation of the bias field $E^{(0)}(t) = E_0^{(0)} + E_1^{(0)}(t)$ where $E_1^{(0)}(t)$ is the given fluctuation function ($E_1^{(0)}(t) \neq 0$ when $t > 0$).
When the solution of Eq. (6) found, the normalized radiation field transmitted through the dielectric mirror is obtained as

$$U_1(t) = (n/n_1) f(\tau - 0.5L - d) \qquad (10)$$

and the current in the active layer is computed as

$$J_S(t) = J_{S0}\left[G\left(E_0^{(0)}\right) + J_1(t)\right] \qquad (11)$$

where

$$J_1(t) = n_1\left[f(\tau) - E_1(\tau_1,\tau_2,\tau_3)\right]. \qquad (12)$$

III. NUMERICAL RESULTS

We simulated the process of self-excitation of electromagnetic oscillations in the cavity with a strong coupling of electromagnetic field and active devices when the coupling constant $G_0 \sim 1 \dots 3$. In terms of Eq. (1), it corresponds to rather large values of the surface current density $J_{S0} \sim 3 \dots 10$ A/cm in the active layer that requires sufficiently dense packaging of the powerful micro-devices in the active array.

In the case of a thick dielectric mirror, the electromagnetic field is efficiently confined in the cavity and the coupling of the field to the active layer is very strong. In this case, the continuous anharmonic oscillations are typically excited when some initial fluctuation of the bias field is applied.

Fig. 3 shows an example of such oscillations when $D = 15\,mm$, $d = 5\,mm$, $n = 2$, $G_0 = 2$ and $E_0^{(0)} = 3$. The basic frequency of oscillations is about $f_0 = 20\,GHz$. The initial fluctuation $E_1^{(0)}(t)$ of the bias field $E^{(0)}$ is shown by the dashed curve.

On the contrary, in the case of a thin dielectric of a small refractive index chosen to be just sufficient to support self-oscillations, a train of ultra-short radio pulses is generated. The train of pulses radiated from such a cavity is shown in Fig. 4. It arises when $D = 15\,mm$, $d = 0.15\,mm$, $n = 2$, $G_0 = 2$ and $E_0^{(0)} = 3$ providing the pulse repetition frequency $f_p = 10\,GHz$ and the carrier frequency $f = 500\,GHz$.

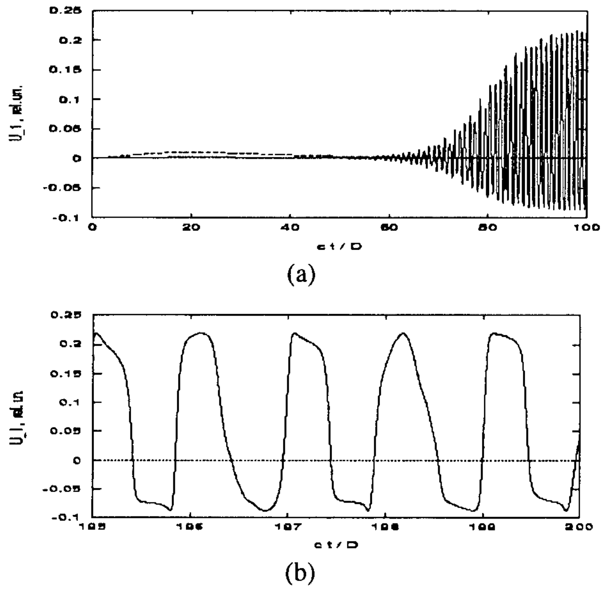


Fig. 3: Radiation field in the case of a thick mirror

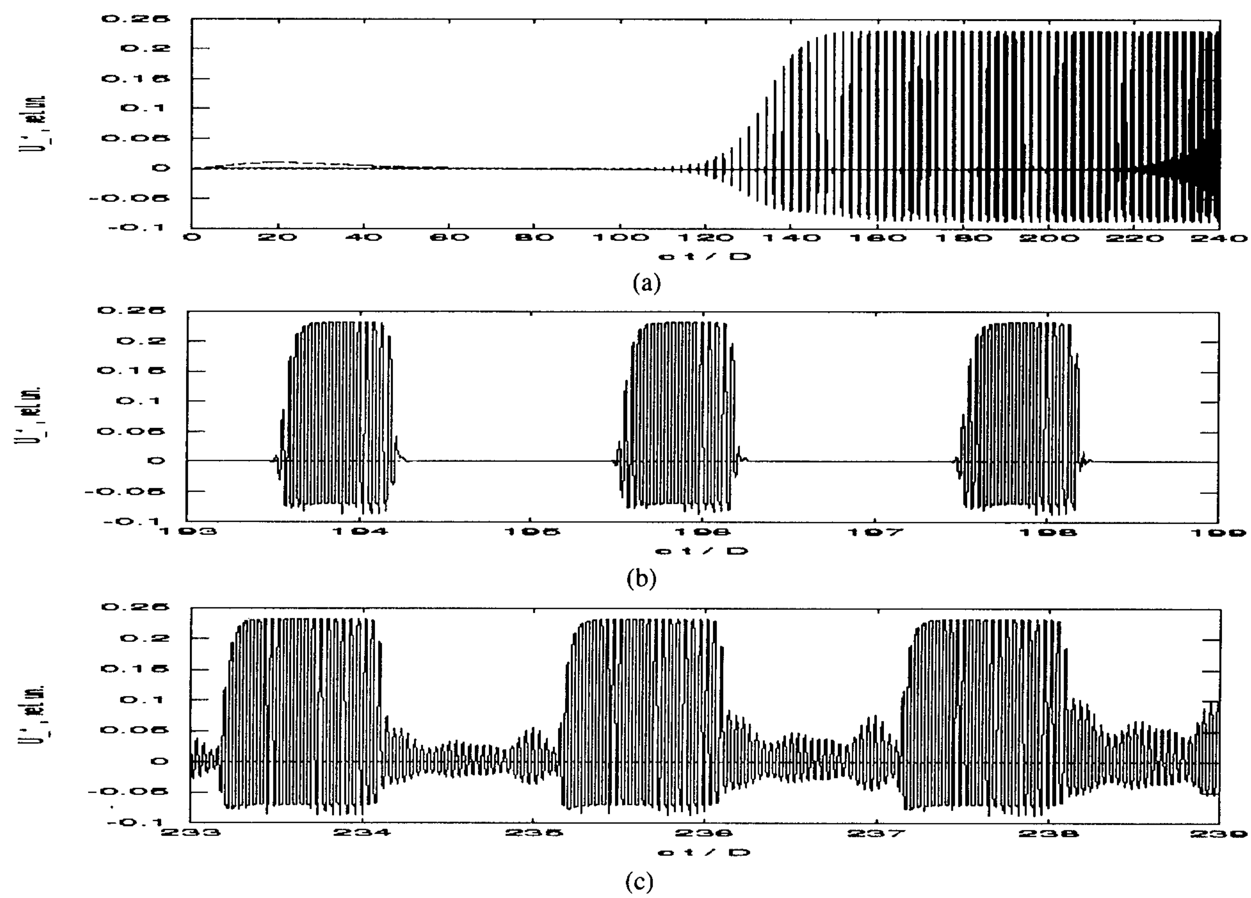
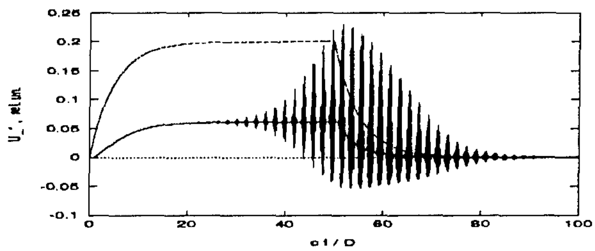
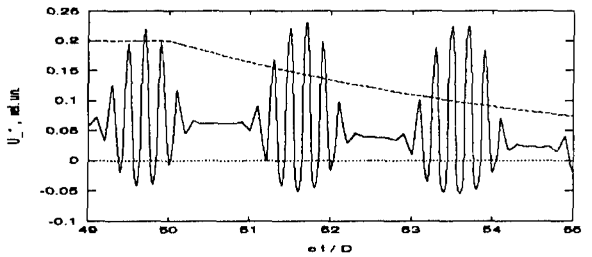


Fig. 4: Radiation field in the case of a thin mirror

The period of pulsing t_p is equal to a single round trip of the field in the cavity, $t_p = 2D/c$. Meantime, the carrier frequency of each pulse, f, is defined by the thickness d and the refractive index n of the dielectric mirror as $f = c/(2nd)$.



(a)



(b)

Fig. 5: The train of ultra-short pulses generated by the pulse of external voltage $E_1^{(0)}(t)$ added to the initial bias $E_0^{(0)}$. The parameters are $D = 15\ mm$, $d = 0.8\ mm$, $n = 1.4$, $G_0 = 2.8$, $E_0^{(0)} = 2.8$ and $E_1^{(0)}{}_{max} = 0.2$ providing the frequency of the pulse repetition within the train $f_p = 10\ GHz$ and the carrier frequency of each pulse $f = 100\ GHz$. Duration of the bias pulse is $T_p = 2.5\ ns$ while the period of pulsing within the train is $t_p = 0.1\ ns$.

The frequency f depends on d and n in such a way that the half wavelength in the dielectric is equal to d. The carrier frequency increases with decreasing d and can be up to a hundred times greater than the frequency of the pulse repetition $f_p = 1/t_p$. For example, in the case shown in Fig. 4, we have $f/f_p = 50$, with the pulse duration $t_0 = 0.4 \times 10^{-10}$ s.

The pulses gradually extend and overlap if the oscillations continue for a long time (Fig. 4, b and c). So, in order to obtain the clear train of pulses, one has to turn off the excitation at some moment by decreasing the bias voltage below the threshold value and then turn on it again by increasing $E^{(0)}$ when the pulses have been radiated from the cavity (Fig.5).

Thus, the bias voltage has to be periodic as well, with the period T_p being much greater than the period of pulses t_p generated within the train.

The process of the excitation of ultra-short radio pulses discussed above is analogous to the generation of short pulses in optics by means of periodic pumping of a short-pulse laser by another laser providing the pump pulses of greater duration.

IV. Conclusion

Numerical simulation of the process of electromagnetic field excitation in a one-dimensional cavity with an active layer and a dielectric mirror has shown a possibility of ultra-short pulse generation in the system.

A solution found for the cavity of the length $D = 15\ mm$ with the dielectric mirror of thickness $d = 0.15\ mm$ and of refractive index $n = 2$, shows the generation of the train of such pulses. The repetition frequency of the pulses within the train is $f_P = 10\ GHz$ while the carrier frequency of each pulse is $f = 500\ GHz$, with the pulse duration $t_0 = 0.04\ ns$.

The excitation of the perfect trains of pulses requires periodic variation of the bias voltage around the threshold value in order to avoid the overlap of pulses within the train. The period of variation is typically large as compared to the duration of a single pulse. So, the train may contain a long sequence of ultra-short pulses.

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